Beware of These Top-10 Issues in Modal Testing

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There is plenty of information that will help you to be careful when you are involved in a modal analysis project – whether it be analytical or experimental. But surely there are some really important items that you need to be aware of when working in this area. While there are many items that could be listed, I am going to make a top-10 list (because 10 seems like a good number to pick). So let's count down these items that I have selected as some of the "top" things to watch out for. So in David Letterman style, "Here we go."

No. 10: Why are you performing this test?

Why ask why? Well that's because it is the most important question to ask. So let me elaborate on this a bit.

Many times we conduct tests because someone believes that the test will solve some problem or that it is a test that someone *thinks* will solve a problem. I have no problem performing a test, but many times people really don't realize what the test may or may not provide. That is the reason for me to always ask "why" to run this test. Is there an operating problem? What additional items are expected from the test? What frequency range is really of interest? How many modes are really of concern? And on and on. So it is really important to find out as much as you can before you run the test to make sure everyone is on the same page in terms of what the test will provide.

And I say it that way because I have seen many instances where people have "claimed" to understand the test and are adamant about what they want from the test and have been very clear as to that. But then once the test results are provided, then there are questions as to why the test does not answer the questions of interest. And sometimes the disconnect occurs because sometimes the words we use may mean different things to different people. So generally I always ask very specifically what people want to know, and I very specifically ask what they mean (with an explanation) by each of the things that they have requested.

As an example, I remember a group of young engineers in the automotive industry wanting to "learn" how to do modal testing and how to "correlate" to a finite-element model for a simple brake rotor configuration. All the right questions were asked, and it seemed like a very good effort to try to understand the very basic material to learn how to take baby steps in understanding what is necessary before undertaking a much more complicated system. OK – so it seemed like all the right discussions were made and everything considered.

But before the project started, this group of young engineers wanted to make a presentation to their management as to what they were about to undertake – again a very good thing to do to get everyone to "buy into" the project. Everything still seemed to be going smoothly until they introduced the project in this way:

> *Hello everyone. This will be a project that will perform testing on a brake rotor to correlate to a finite-element model. The results of this project will solve our brake squeal problem.*

And that was the first time they mentioned brake squeal. So suffice it to say, the squeal problem and what was originally discussed were completely disconnected.

So why ask why? That is exactly why!

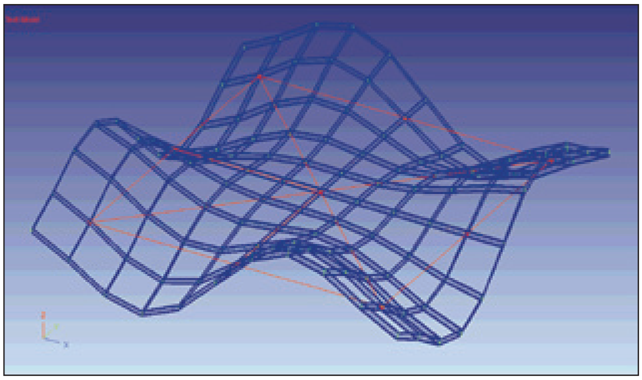

Figure 1. Nine measurement locations – unfortunately all located at the nodes of this particular mode.

No. 9: Selecting Appropriate Test Points

Often I see people start a modal test, and they get all wound up selecting all the points for measuring and make an elaborate geometry file and get all the coordinates lined up – but they haven't taken a single measurement.

Before you go head over heels making a geometry, go out and make a measurement first. Actually make a few measurements. Check different measurement locations and in different directions. This is critical, especially if you really don't know what all of the modes of the system might be. It doesn't make any sense to select all the points until you have some idea what all the modes might be for the system.

Often the points you think you need to measure may not actually be the best locations, depending on the modes of the system. Somehow, in my mind, I think that the FRF (Frequency Response Function) will tell you so much about the structure and frequencies that you really need to worry about that first.

Then maybe take just a handful of measurements to make sure you really do know what the mode shapes might be for the structure. Once you are sure you know what all the mode shapes might be, then you can select many more measurements, but with the understanding of what the shapes might be. Too often I have seen people identify 100 to 150 points, run the modal test, curvefit the data, and then all sit looking at the mode shape only to realize that they placed all their measurements on a portion of the structure that really has very little to do with the modes of interest for that structure.

Also be sure that your reference location for your FRF measurements is at a location(s) where you know that you can see most if not all of the modes. Certainly if all the modes cannot be seen, then it is imperative that additional references be used. When performing impact testing, it is always advisable to use as many references as possible.

If you have a four-channel system, then you should have one channel for the hammer and three references on the structure. They don't have to be oriented into each of the three directions – X, Y, Z. But you want to make sure that they are all located to see as many of the modes of the system as possible.

If you have an eight-channel system, then use seven references if you are doing a roving-impact test. You might think it is overkill, but it really doesn't take much additional effort to collect the data. It never hurts to have more data.

And you think with seven references you would get all the modes – well most times you would think so. But I can recall one test on

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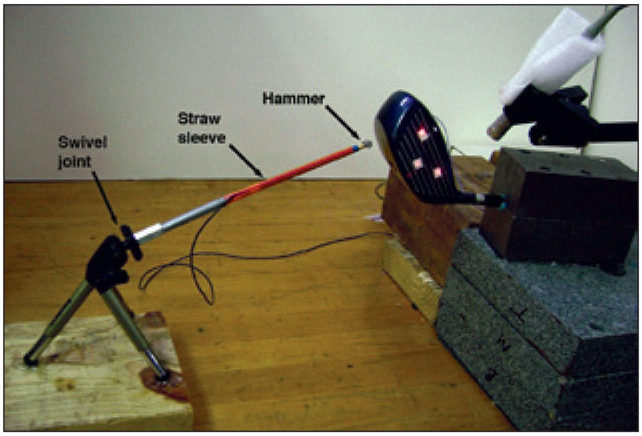


Figure 2. Impact hammer test configuration.

a large symmetric composite plate structure where nine reference accelerometers were used to run the test. But as it turned out, one of the higher modes was missed because all of the nine accelerometers ended up located at the nodes of this higher mode. Who would ever guess you could be that unlucky? (I recommended that this person never gamble in Las Vegas, because his luck was obviously bad.) The higher-order mode and the measurement locations for the nine accelerometers are shown in Figure 1.

No. 8: Hammer Tip Selection

Now selecting the proper hammer tip can sometimes be confusing to the novice. Basically what you want to do is make sure that you select a hammer tip that will excite a frequency range similar to the range of frequencies that will be excited when the structure is in service. Of course that means that you have to have some idea what frequency range is really important.

Many years ago when we started doing some modal testing on baseball bats, there was a very long discussion as to what would be the best tip to use. I explained that you needed to have a hammer tip that would excite a similar range of frequencies as those excited by the actual ball hitting the bat. When I arrived to the lab the next day, the students had taken a baseball and put a 10-32 tapped stud into the baseball and then screwed that onto the hammer. Of course, this was a brilliant idea, because it is as close as we can get to the actual impact scenario for the ball hitting the bat.

But you also have to remember that the hammer tip is not the only thing that controls the input force spectrum. The local flexibility of the structure can also play a critical role in the actual force spectrum imparted into the structure for the modal test. So you really need to look at this closely. And by the way, you can take those published curves you get from the hammer manufacturer and just put them aside, because those are all generated by impacting a massive, stiff, steel block that is never what we actually have when we perform a modal test.

Another critical item in impact testing that is often not taken seriously is that the hammer must impact the structure *consistently* with the same point impacted in the same direction for every measurement. If this is not done, then the FRF will have some variability between each measurement and result in reduced coherence. On a large structure this may not be hard to do. However, on a smaller structure this can be difficult. One test for a golf club head used a unique tripod/hammer configuration to consistently impact the same point in the same direction for every measurement (see Figure 2).

No. 7: How Free Does It Need to Be?

There have been a few articles on this subject. The most important thing to realize is that your test article is actually your structure plus all the instrumentation and support conditions. The finite-element model of your structure can be modelled as free, but the reality is that there are soft springs that really need to be included in the model to properly account for the support system for your structure along with all the instrumentation added. Many times this does not affect the overall test, but in many cases, this is actually very important to include in your analysis of the structure.

Figure 3a. Impact test on missile hung at locations close to the nodes of the first bending modes.

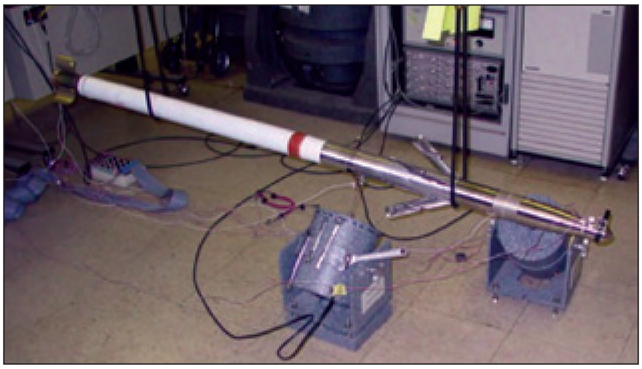


Figure 3b. Shaker test on missile hung at locations close to the nodes of the first bending modes.

But what you really want is for the rigid-body modes of your structure to be reasonably well separated from the flexible modes and have little modal overlap or coupling between the rigid-body and the flexible modes. While this is very easy to say, this is not always easy to achieve. Most times I recommend that the finite-element model include the effects of the support structure in the model to get a clear understanding of how the test setup might interact with the test article. While the finite-element model may not be perfect, the model is a great way to study the effects of stiffness changes in the support structure and the corresponding effect on the flexible modes of the system overall.

If there is no model available, then this needs to be checked when the test is set up to identify exactly what the interaction might be for the test configuration. This might take some extra effort, but it is a critical part of the test setup that needs to be documented and identified.

A test where this was of concern was when missiles were tested. It is very hard to get them into a free-free condition. So the best we can do is to test the missile hung from a gantry and perform the test with the missle supported at the nodal locations for the first flexible mode. Then the support condition is not very intrusive, because it is supported at the node of the mode. Figure 3a shows a typical missile configuration with Dilbert performing the impact test here; Figure 3b shows a smaller missile undergoing shaker modal testing.

No 6: Other Common Blunders

There are always some of the most simple things that often get overlooked. These are the simple sanity checks to make sure that everything is set up properly.

Make sure all cables are good and have not been crimped or bent and that all the connectors are tightly connected. Often spurious signals, especially with the impact hammer, may be the result of a loose cable connection.

Of course make sure all your signal conditioners are turned on and that you understand if your transducers are either voltage or ICP. I have seen many tests run where the ICP transducers were set as voltage transducers, and the measurements are essentially useless. Of course you would have expected that the measurements would not look good but if you go into the measurement process assuming that you have a very complicated, nonlinear, heavily damped system, then you are expecting your measurements to not look good.

Of course if the measurement system is not set up properly, your measurements won't look good. Therefore you may think that this is the best you can do – even though your measurements are terribly wrong.

You also have to realize that if you only own one hammer, that does not mean that it is useful for *all* the tests you plan to conduct. I have seen people violently wailing away on a large structure with an impact hammer that is clearly too small to excite the structure and insufficient to conduct the test. (And believe me, I have seen some hammer tips that are so battered that the appear to have been exposed to a nuclear blast.) Get an appropriatley sized hammer to conduct the test you need to perform rather than try to use an inappropriate hammer for the test.

Another important consideration is in regard to the size of the accelerometer that is used. Mass loading can be a very important consideration. There have been many articles written to understand these effects. This needs to be addressed and documented. Just because it is the smallest accelerometer that you own does not mean that the mass loading is not of concern. And it is not just the mass of the accelerometer relative to the total mass of your test structure – it is the mass relative to the effective mass of the structure where it is mounted. An accelerometer weight at a very stiff/massive location on a structure is different than that same accelerometer mounted on a thin lightweight flimsy panel in the same structure.

And one more important item is that you need to make sure that you have not saturated your transducers, in which case they will not be able to provide useful measurements. I have been party to tests where people have bought very sensitive transducers because they think they are "better," but then they find out that their structure is very responsive, and the response saturates the transducer.

No. 5: Double Impacts

Now we really do want to avoid double impacts if at all possible. But there will be many instances where we just can't avoid them. So try your best to impact with single impacts. But if you do have a double impact, then the thing to do is look at the input power spectrum of the force hammer. As long as the force spectrum is reasonably flat and there is no significant dropout in the force spectrum and the FRF/coherence looks good, then most likely the measurement will be adequate for the test to identify the frequencies and mode shapes.

But of course you can ask how flat does the force spectrum need to be and how much of a drop in the force is tolerable? And these are good questions to ask. I would rather not see the force spectrum drop more than 5 to 10 dB, but as long as the coherence is good, the FRF may be acceptable for a measurement.

I know some people might argue and say that much of a drop is totally unacceptable. But if you look back in some of the *Modal Space* articles we have presented, we have shown that the frequencies and mode shapes were actually very acceptable when comparing a test with no double impacts and a test with several or even quite a few double impacts. But you still need to be very careful to make sure that the data are useful.

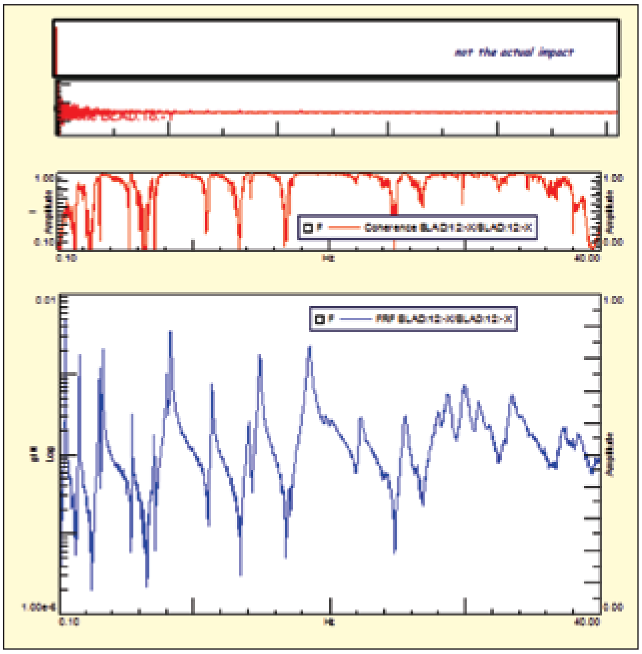


Figure 4a. Single impact FRF for large wind turbine blade.

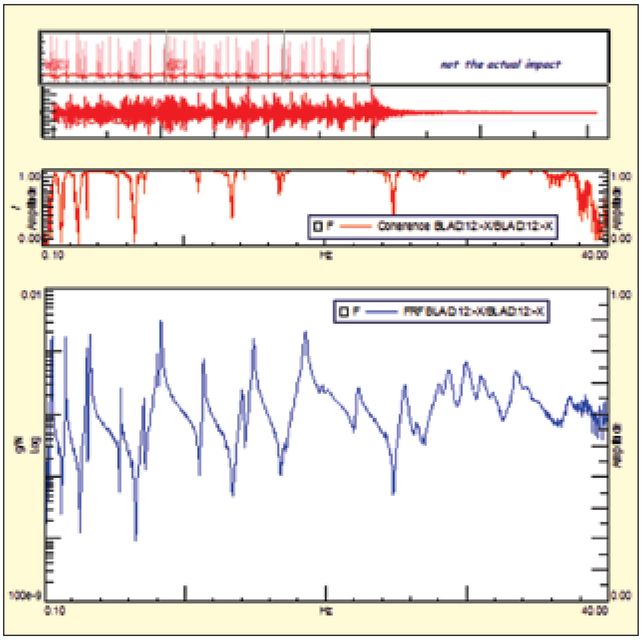


Figure 4b. Multiple-impact FRF for large wind turbine blade.

And just for the record, there were a few articles that discussed double impacts and one article where multiple impacts were intentionally applied to the structure for a "burst-impact" excitation test. While that was shown on an academic structure, over the past year we actually tested a large radio telescope and a large (50 m+) wind turbine blade and very cleary showed that the multiple-impact technique provided far superior results. The measurement in Figure 4a and 4b shows the result of an FRF measurement on a very large wind turbine blade with the coherence. The first measurement (4a) is made with a single impact, and clearly the variance on the FRF measurement and the coherence show that the measurement is contaminated with noise. But the next measurement (4b) shows the result for the multiple impact, and it is very obvious that the FRF and coherence are dramatically improved using the multiple-impact technique. Of course you need take care and assure that the entire input and output are observed within one sample interval of the FFT time window. If that is done, the measurement can be very much improved.

No. 4: Windows

I am sorry to say that as far as I am concerned, no window is a

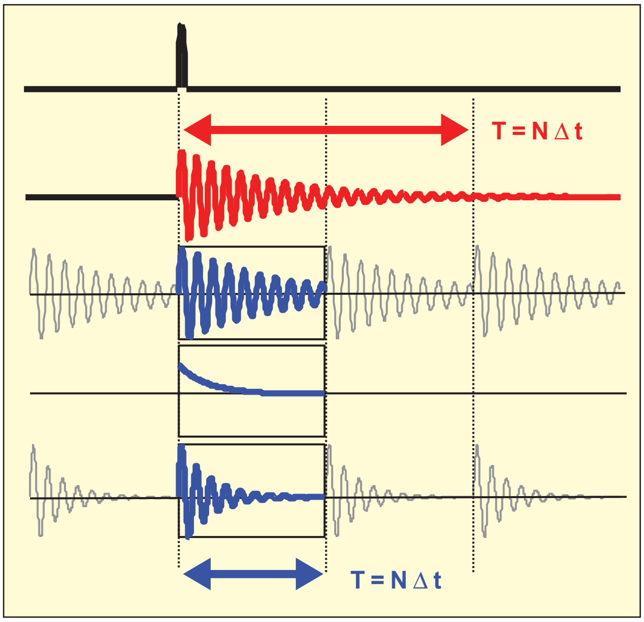
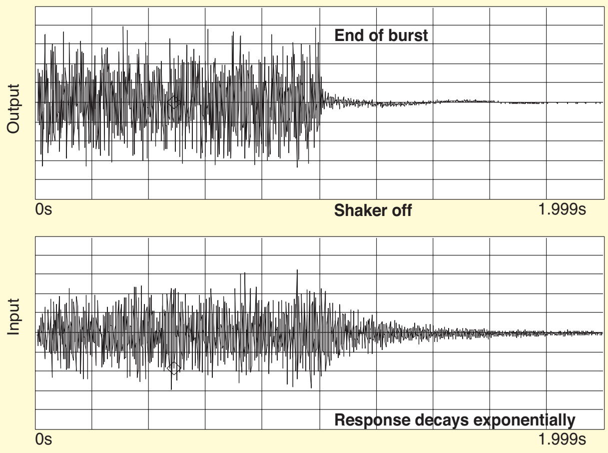


Figure 5. Window required for shorter time sample (blue) can be eliminated by changing time sample (red).

(a) Time signal



(b) Frequency signal

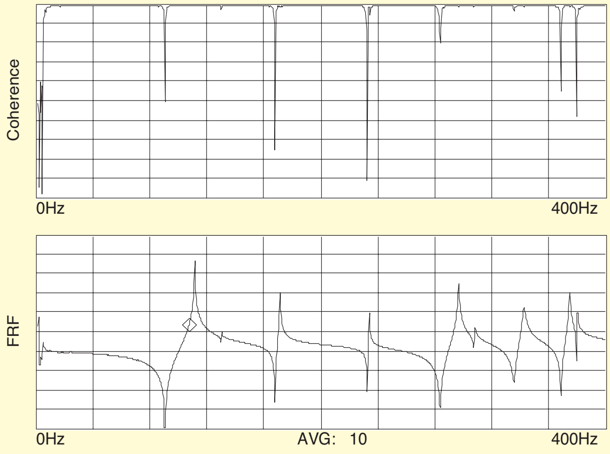


Figure 6. Example of shaker excitation (burst random), which provides leakage-free FRF measurement.

good window (a window distorts data), but windows are a necessary evil. These are strong statements that I live by.

Do everything possible to assure that your input signal and response signal are either periodic in the sample window or entirely captured within the sample interval. If you can do this, then you don't need to use any window.

When performing impact testing, always try to change the acquisition parameters so that the signal can be completely observed in one sample interval of the measurement process. If this can be done, there will not be any leakage, and a window is not needed. Figure 5 shows how by simply changing the sample time, the need for a window can be eliminated.

And actually the same is true for shaker testing. But in this case, we try to create a sample of data that is completely measured within one sample of collected data (the same as was done in the impact just described). *Or* in shaker testing, the other option is to create an excitation signal that forms a response that repeats. If this can be done, the system will get to steady-state response, and then the Fourier transform will be satisfied, leakage will not be a concern and a window will not be needed.

In shaker testing, many signals will create this situation and are used often in shaker testing. These signals are specialized for modal testing – pseudo-random, random transient, burst random and sine chirp are all signals that were created specifically for this type of modal testing. Figure 6 shows the most commonly used burst random excitation that provides an excitation that starts and ends within one sample interval of the time sample for the FFT. Therefore it does not need a window, because there is no leakage of concern. Providing that the response also starts and ends within the time sample, then a window is not needed on the response either. So this excitation has no leakage, and no windows are required.

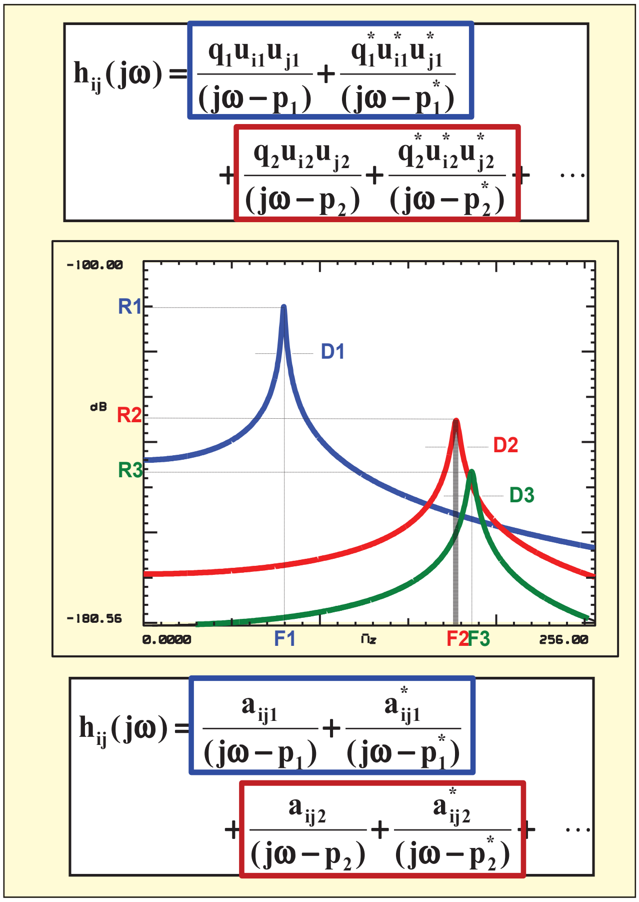
No. 3: Modal Impact Test Setup Ritual

So every time I set up to perform an impact test, there is a ritual that I usually go through to make sure that I can make the best possible FRF measurements. There isn't a specific set of steps that I take every time I do this but there are certainly key things that I do every time I make a measurement. Of course, I am talking about taking a measurement on something that I have never tested before or something that is completely new to me. (If it is a structure that I test every day, then maybe some of these steps will not be needed, because I have *a priori* information that gives me a good understanding of what is expected.)

So when I start a measurement, I never take anything for granted and I start with a measurement with a frequency bandwidth that is higher than the frequency range that everyone *believes* is the frequency range of interest. I then use a hammer tip to excite the structure over this range of interest, and I always check the input power force spectrum applied to the structure under test. Of course, while I make this first measurement, I may need to adjust the voltage level for the hammer input as well as the accelerometer responses. This may need to be done manually unless your acquisition system has provision to "auto-range" all the response levels. Of course at this point, I may need to change the hammer tip to excite the appropriate frequency range of interest and then check to make sure that all the proper response ranges are still appropriate as the different hammer tips are studied.

Once we have a good input excitation, then we will start to look at the response, FRF and coherence. But the first thing to do is to look at the response decay to see if the entire response can be captured within one time sample of the measurement. If this is satisfied, then we do not need to apply a window. If it is not satisfied, then we might want to consider a longer time window. If this is not possible, then we might need to apply a window, which in this case would be an exponentially decaying window.

Once this is done, then we would want to take several averages to look at the FRF and coherenece. If this is an acceptable measurement, then the next step would be to change the hammer tip to excite a slightly lower frequency range. Remember that when I started this process, I selected a higher frequency range than what may have been prescribed for the test. So this is a good opportunity to make sure that the hammer tip is actually exciting the frequency range of interest, because the frequency range is still set for the higher frequency range. Now that less input force is being applied to the structure, it is important to make sure that all the voltage ranges are still set properly and that the damping window if originally used is still necessary along with other parameters set for the initial set of tests. Once this is all checked, then a measure-



$$h_{ij}(j\omega) = \boxed{\frac{q_1 u_{i1} u_{j1}}{(j\omega - p_1)} + \frac{q_1^* u_{i1}^* u_{j1}^*}{(j\omega - p_1^*)}} + \boxed{\frac{q_2 u_{i2} u_{j2}}{(j\omega - p_2)} + \frac{q_2^* u_{i2}^* u_{j2}^*}{(j\omega - p_2^*)}} + \cdots$$

$$h_{ij}(j\omega) = \boxed{\frac{a_{ij1}}{(j\omega - p_1)} + \frac{a_{ij1}^*}{(j\omega - p_1^*)}} + \boxed{\frac{a_{ij2}}{(j\omega - p_2)} + \frac{a_{ij2}^*}{(j\omega - p_2^*)}} + \cdots$$

Figure 7. Frequency response function written on a mode-by-mode basis using residue and mode shape formulation.

ment would be made to assess the FRF and coherence.

Following this, the frequency range of the FFT analyzer could be changed to the lower frequency range associated with the actual softer hammer tip excitation range of the last measurement. Again, all the same parameters would need to be checked to make sure that an appropriate level is set and a good measurement is obtained.

So for the measurement process I just described, you can see that all of the parameters need to be checked each time I change each and every one of the individual items that can change. Remember that I have the ability to change the bandwidth of the measurement, the number of spectral lines, the hammer tip and the use of windows, if needed. All of these need to be considered when making the measurement. And I keep changing all these parameters until I am happy with the measurement that has been made. At this point, I would start to collect sets of measurements for the experimental modal test.

No. 2: $U_i \times U_j$

Now this is probably the biggest item to consider, but what does it mean. Well let's write an equation down to explain what this means. The FRF can be written in terms of residues or in terms of mode shapes (and has been used in many different *Modal Space* articles in the series), as shown in Figure 7.

The lower equation is the common way that it is normally written in most of the literature. This is useful but only if you really understand what a residue is. The upper equation is actualy the same equation but with the residues expressed in terms of mode shape information. Specifically the residue (directly related to the amplitude of the frequency response measurement) is related to the value of the mode shape at the input excitation location times the value of the mode shape at the output response location for a particular mode of interest and will determine the amplitude of the frequency response function for that particular mode. Of course the effects of all the modes are the linear summation of all the modes of the system.

The Rules of Modal
(At least from a student perspective)

1. The Big Dog has great advice
2. $u_i \cdot u_j$
3. $u_i \cdot u_j$
4. See Rules 2 and 3
5. Don't ask the Big Dog a question unless you want more project work
6. Don't ask the Big Dog a question if you plan to leave within 30 minutes
7. In one breath, you must be able to say: "The magnitude of a complex number is the square root of the sum of the squares of the real and imaginary parts"
8. In the same breath, you must be able to say: "No window is needed provided that it meets the periodicity requirement of the Fourier transform process"
9. Document everything
10. And then document that

So what does this tell me? Basically it gives a very clear definition of the peak amplitude of the FRF related to the values of the mode shape for a particular mode at the input-output location.

At times people ask why the amplitude of a particular mode is very low for a particular measurement. Well, this equation tells me that for that particular mode, either the input excitation or output response (or both) is a very small value and probably close to the node of a mode. If you want to see that mode with a more pronounced peak in the FRF, you really need to change the input and/or output location to be at a place where the mode shape values are much larger and away from the node points.

And actually if you want to conduct a test and select good locations for measurements, then you really need to look to see where the mode shapes are large for each of the modes of the system. The finite-element model is a very good tool to use to help decide where to place all the transducers. While the model may not be perfect, certainly it is a reasonable representation of your structure under test.

I think if you look at a good number of all the articles in the *Modal Space* series, you will find that this is a theme for many of them. Firmly understanding this principle will be a great asset to your understanding of many questions that arise in the conduct of an experimental modal test.

Actually the students in the lab have a list of their top-10 things from their perspective of what I always say. You can see that Numbers 2 and 3 and the follow up 4 pretty much say that this is one of the critical rules of modal and that it is likely the answer to many of your questions. Drum roll, please . . .

No. 1: Thinking is Not Optional

OK, so now let's talk about the *numero uno* . . . and that is to realize that you really need to think about what you are doing all the time when you perform testing or analysis. None of this is mundane and thinking is required. This is not like you are working at Burger King, where everything is all so very clearly defined. Burger, fries, coke . . . push the button and the price is determined without any thought at all.

Once you stop thinking and just blindly follow a set of rules, then you are likely to fall into the hand of the *Modal Monster*, and your results may not be useful if you have encountered any problems that really required your attention and some thinking to realize what may have happened with your measurement.

Don't let the *Modal Monster* rule – understand what you are doing, think always, question assumptions, and be vigilant when you are making measurements and conducting modal tests. For sure go back and read all the *Modal Space* articles. There are many important issues that may help answer some of your questions and concerns.

I hope that this last bit of advice helps many of you. If you have any other questions about modal analysis, just ask me. Or go to our webpage: http://www.uml.edu/SDASL. S/V

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